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CHEMICAL SIGNATURES OF THE FIRST GALAXIES: CRITERIA FOR ONE-SHOT ENRICHMENT

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ABSTRACT

We utilize metal-poor stars in the local, ultra-faint dwarf galaxies (UFDs; $L_{\rm tot} \leqslant 10^5\,L_\odot$) to empirically constrain the formation process of the first galaxies. Since UFDs have much simpler star formation histories than the halo of the Milky Way, their stellar populations should preserve the fossil record of the first supernova (SN) explosions in their long-lived, low-mass stars. Guided by recent hydrodynamical simulations of first galaxy formation, we develop a set of stellar abundance signatures that characterize the nucleosynthetic history of such an early system if it was observed in the present-day universe. Specifically, we argue that the first galaxies are the product of chemical "one-shot" events, where only one (long-lived) stellar generation forms after the first, Population III, SN explosions. Our abundance criteria thus constrain the strength of negative feedback effects inside the first galaxies. We compare the stellar content of UFDs with these one-shot criteria. Several systems (Ursa Major II, and also Coma Berenices, Bootes I, Leo IV, Segue 1) largely fulfill the requirements, indicating that their high-redshift predecessors did experience strong feedback effects that shut off star formation. We term the study of the entire stellar population of a dwarf galaxy for the purpose of inferring details about the nature and origin of the first galaxies "dwarf galaxy archaeology." This will provide clues to the connection of the first galaxies, the surviving, metal-poor dwarf galaxies, and the building blocks of the Milky Way.

Key words: dark ages, reionization, first stars – early universe – galaxies: dwarf – stars: abundances – stars: Population II

Online-only material: color figures

1. INTRODUCTION

One of the important unsolved problems in cosmology is understanding the formation of galaxies (e.g., Benson 2010; Mo et al. 2010). To make progress on this complex issue, it is advantageous to investigate simple systems that allow us to study the basic processes that led to their origin and evolution. Dwarf galaxies are such objects and can be studied both observationally and theoretically (Mateo 1998). They are generally old, metal-poor, have no gas, and thus no longer support star formation (Tolstoy et al. 2009 for a review). These conditions make them ideal candidates to constrain theoretical models for star and galaxy formation in the early universe (Bromm & Yoshida 2011). One particularly important question is to elucidate the role of feedback processes in galaxy formation (see Silk 2011). Again, early dwarf galaxies may provide us with an ideal laboratory to test the physics of feedback (e.g., Dekel & Silk 1986; Ciardi & Ferrara 2005; Mashchenko et al. 2008; Maio et al. 2011).

In particular, the population of faint dwarf galaxies discovered in the Sloan Digital Sky Survey (SDSS) that surround the Milky Way (MW) offers a unique way to investigate these topics. Due to their simple nature, these so-called ultra-faint dwarf galaxies (UFDs), here defined to have $L_{\rm tot} \leqslant 10^5\,L_\odot$ (Martin et al. 2008), are the closest local analogs to the first galaxies. They are believed to have had only one or a few early star formation events, but have been quiescent ever since (e.g., Koch 2009). Hence, they should retain signatures of the earliest stages of chemical enrichment in their stellar populations. Indeed, these systems are very metal-poor and extend the metallicity–luminosity relationship of the classical dwarfs down to $L_{\rm tot} \sim 10^3\,L_\odot$ (see Kirby et al. 2008 for more details). High-resolution spectroscopy (Frebel et al. 2010b; Norris et al. 2010c; Simon et al. 2010) further showed that the abundances of faint dwarf galaxy stars resemble those of similarly metal-poor Galactic halo stars. This suggests that chemical evolution is universal, at least at the earliest times which are probed by the most metal-poor, and thus presumably the oldest, stars. The same chemical trends have also been found in a few stars with $-4.0 \leqslant$ [Fe/H] $\leqslant -3.5$ (Frebel et al. 2010a; Tafelmeyer et al. 2011) located in the more luminous, classical dwarf spheroidals (dSphs) Sculptor and Fornax. However, at higher metallicity ([Fe/H] $> \sim -2.5$), the stellar ([α/Fe]) abundances of both systems deviate from those of Galactic halo stars (e.g., Geisler et al. 2005), indicating a different evolutionary timescale and multiple star formation events leading to extensive metal-rich stellar components (Tolstoy et al. 2004). This high level of complexity has been established for all the classical dSphs down $L_{\rm tot} \sim 10^5\,L_\odot$, making it difficult to directly connect them to the first galaxies.

The UFDs thus provide us with a tool for performing "dwarf galaxy archaeology." This terminology builds on the more general concept of "stellar archaeology" which posits that the chemical composition of the early universe is preserved in the atmospheres of individual metal-poor stars. Specifically, dwarf galaxy archaeology involves the *entire* stellar content of a dwarf galaxy, including the more metal-rich stars, in contrast to the focus on single metal-poor stars in the traditional approach. With their relatively limited number of stars, the least luminous galaxies are ideal candidates for dwarf galaxy archaeology. As opposed to the MW halo, which was assembled through multiple merger and accretion events, the lowest luminosity dwarfs likely did not form via extensive hierarchical merging (Wise & Abel 2007; Greif et al. 2008; Bovill & Ricotti 2009). Their entire stellar population, therefore, directly traces early star and galaxy formation. The more metal-rich stars, with [Fe/H] $\gtrsim -2.0$, in these faint metal-poor galaxies will provide the strongest constraints on the star formation history, and hence the formation and evolution of the host system.

In particular, dwarf galaxy archaeology facilitates establishing the connection between the surviving UFDs, the first galaxies and the building blocks that formed the MW halo. This is important since recent abundance studies have suggested early, accreted analogs of today's UFDs to have played a significant role in building up the metal-poor tail of the Galaxy (Frebel et al. 2010b; Simon et al. 2010; Norris et al. 2010c). The Galactic halo contains a significant number of extremely metal-poor stars (with [Fe/H] < -3.0; e.g., Beers & Christlieb 2005), including some objects with [Fe/H] < -5.0 (Christlieb et al. 2002; Frebel et al. 2005). Their abundances have been attributed to individual Population III (Pop III) SN yields (e.g., Umeda & Nomoto 2003; Tominaga et al. 2007), which provide a key empirical diagnostic for Pop III nucleosynthesis and overall constraints on the nature of these progenitors. Consequently, since these stars are likely nearly as old as the universe, their origin may reside in small, early systems. A better understanding of this connection is vital for understanding chemical enrichment and star formation in the very early universe (Karlsson et al. 2012).

In this paper, we specifically suggest that the stellar abundance record preserved in the metal-deficient dwarf galaxies contain crucial hints on how effective early feedback effects were in suppressing star formation. This endeavor is complemented by the confluence of two recent developments: the availability of large-scale parallel supercomputers allowing ever more realistic simulations of early structure formation, and increasingly detailed observations of stars in these UFDs.

2. COSMOLOGICAL CONTEXT

The purpose of this section is to summarize those aspects of recent ab initio simulations of first galaxy formation (see Bromm & Yoshida 2011 for a review and further references) that provide us with the theoretical underpinning and guidance in formulating potentially observable chemical abundance signatures that may be found in a first galaxy. We begin by discussing ideas on where the first stars and galaxies form, and then turn to early metal enrichment.

2.1. Early Star Formation Sites

In a ΛCDM universe, structure formation proceeds hierarchically, with small dark matter halos merging to form larger ones. The first stars are expected to form in minihalos, collapsing at $z \simeq 20$–30 (Tegmark et al. 1997) and comprising masses of $\sim 10^6\,M_\odot$. These minihalos host a small multiple of predominantly massive Pop III stars (Turk et al. 2009; Stacy et al. 2010). The individual masses of these first stars are thought to be of the order of $\sim 100\,M_\odot$ (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2008), distributed according to a still uncertain initial mass function (IMF). It is likely, however, that a range of masses toward lower and higher values would have been present (e.g., Clark et al. 2011; Greif et al. 2011). Massive Pop III stars will exert strong feedback on their host halos and the surrounding intergalactic medium (IGM), through both radiative and SN feedback (Bromm et al. 2003; Ciardi & Ferrara 2005; Alvarez et al. 2006), removing gas from the shallow potential well of the minihalo, thereby quenching star formation.

A second round of star formation must have occurred in more massive systems whose deeper potential wells were able to reassemble the photo- and SN-heated gas from the diffuse IGM. It has been argued that this can occur within so-called atomic cooling halos (Oh & Haiman 2002), having total masses of $\sim 10^8\,M_\odot$ and collapsing at redshifts of $z \simeq 10$–15. Such systems have virial temperatures of $T_{\rm vir} \simeq GM_h m_{\rm H}/(R_{\rm vir} k_{\rm B}) \sim 10^4$ K, where M_h and $R_{\rm vir}$ are the halo mass and radius. At these temperatures, the gas can cool via excitation of atomic hydrogen lines, without molecular hydrogen. Atomic cooling halos have been proposed as the sites of the first bona-fide galaxies (Bromm et al. 2009), where a "galaxy" connotes a long-lived stellar system which can sustain an interstellar medium, and extended, self-regulated, episodes of star formation.

2.2. Early Metal Production

Assuming that they are plausible candidates for UFD progenitors, hydrodynamical simulations of the formation of atomic cooling halos prior to reionization are ideal for developing an understanding of the nature of the building blocks and their connection to the first galaxies, as well as any surviving dwarf galaxies. Since the simulations are approaching the goal of ab initio calculations without the need for recipes to model star formation and feedback effects (Wise & Abel 2007, 2008; Greif et al. 2010), the results are not affected by a particular prescriptions for these processes.

Simulations indicate that an atomic cooling halo has of the order of 10 progenitor minihalos (Wise & Abel 2007; Greif et al. 2008). Each minihalo in turn will harbor of the order of one SN explosion. The latter prediction is robust, and does not rely on a detailed knowledge of the Pop III IMF. A minihalo will have a few $1000\,M_\odot$ of cold, dense gas available for star formation (Yoshida et al. 2003, 2006). Assuming a star formation efficiency of the order of 10%, one has a few $100\,M_\odot$ in stars. For a top-heavy IMF, this would result in of the order of one SN; for a normal, Salpeter-like IMF, one needs $\sim 100\,M_\odot$ of stellar mass to trigger one SN. In both situations, we would have the same number of SNe per minihalo. Consequently, a given Pop II star that formed in an atomic cooling halo would be enriched by at most ~ 10 SNe, with an element distribution that depends on the details of the turbulent mixing of the metals.

One key simulation result is that the center of the emerging atomic cooling halo is already enriched with heavy elements, to average levels of $\sim 10^{-3}\,Z_\odot$, but with a spread of roughly ± 1 dex around this mean (Greif et al. 2010; Wise et al. 2012). Overall, this level of enrichment appears to be a robust expectation (Johnson et al. 2008). Moreover, this spread could only be prevented in cases where a strong Lyman–Werner radiation background is present, so that H_2 can be destroyed inside the progenitor minihalos, suppressing star formation and concomitant metal enrichment prior to the collapse of the atomic cooling halo (e.g., Haiman et al. 1997; Johnson et al. 2007). However, this situation is thought to be quite rare (Dijkstra et al. 2008). The typical atomic cooling halo will therefore already be metal-enriched, and will eventually host Pop II stellar systems. The enrichment history prior to the formation of those second-generation stars is thus relatively simple, and solely determined by massive SN yields.

Atomic cooling halos, at least at the low-mass end, may thus provide environments for chemical "one-shot" events: their Pop II starburst, synchronized to within roughly the dynamical time of the central gas cloud of a few 10^5 yr (Greif et al. 2008) might be able to drive any remaining gas out of their shallow potential wells. This conjecture needs to be tested with forthcoming highly resolved simulations of the central starburst. To foresee the outcome, we consider the following approximate arguments: just prior to the onset of the initial starburst, of the order of $10^5\ M_\odot$ of cold, dense gas would have assembled. Again assuming a star formation efficiency of 10% on these scales, we expect a star cluster of total mass $\sim 10^4\ M_\odot$ to form. Such central clusters would have luminosities of 10^3–$10^4\ L_\odot$, similar to the total stellar luminosity observed in UFDs (e.g., Martin et al. 2008). For a standard IMF, the starburst would be accompanied by $\sim$100 core-collapse SNe with an explosion energy of $\sim 10^{51}$ erg each. The total SN energy would then be comparable to the gravitational binding energy of an atomic cooling halo at $z \simeq 10$ (Mackey et al. 2003), rendering a complete removal of all remaining gas at least plausible. A second feedback effect that will act to evacuate the post-starburst halo is heating due to photoionization (Johnson et al. 2009).

Such simple, postulated one-shot enrichment systems are the "Rosetta Stone" of cosmic chemical evolution. If still observable, they would be ideal objects for carrying out dwarf galaxy archaeology. Their surviving Pop II stars would preserve the yields from the initial Pop III SNe that had occurred in the progenitor minihalos without any subsequent enrichment from events that operate on timescales longer than the short dynamical time, such as Type Ia SNe or asymptotic giant branch (AGB) winds. A possible caveat that could act to mask the Pop III SN yields is pollution of these ancient stars with accreted interstellar material. However, such contribution is likely extremely small, and can therefore be neglected (e.g., Frebel et al. 2009).

3. CRITERIA FOR ONE-SHOT ENRICHMENT

Assuming the one-shot enrichment scenario, we now discuss what kinds of chemical signatures might occur in a first galaxy. We highlight specific abundance predictions throughout this section.

According to the simulations (see Section 2), any first galaxy is expected to have been chemically enriched by one or a few SNe, but no more than $\sim$10, corresponding to the number of precursor minihalos. To bracket the uncertainties in the primordial IMF, we consider two SN types occurring during the assembly of a first galaxy: conventional core-collapse SNe in the mass range of 10–140 $M_\odot$ and pair-instability supernovae (PISNe) occurring between 140 and 260 $M_\odot$. Since PISNe are assumed to be rare, we expect that no more than one minihalo hosted such an explosion, whereas all other events were core-collapse SNe. Such a distribution can be regarded as an example of early chemical enrichment, but different proportions of the two SN types are of course possible. For simplicity, we do not consider such cases here. We note, however, that any stars with $>260\ M_\odot$, while perhaps present in minihalos, would directly collapse into black holes and thus not contribute to the enrichment. The bulk of the metals is contained in $\sim 10^5\ M_\odot$ of gas, the typical mass of a star-forming cloud in an atomic cooling halo (Greif et al. 2010).

We now consider the likely chemical signature of the second-generation, low-mass metal-poor stars in the first galaxy. Since these objects would be long-lived and thus still be observable today, they provide a fossil diagnostic of these early systems. *According to the one-shot scenario, no subsequent SNe would have contributed to the chemical inventory after the formation of the next (i.e., second) generation of stars.* This second generation included the first low-mass stars whose atmospheric abundances should thus preserve the chemical signatures of the Pop III progenitors.

Typical core-collapse SNe produce $\sim$0.1 $M_\odot$ of Fe (Heger & Woosley 2010). Considering the canonical example of diluting this mass of Fe into a hydrogen gas of $10^5\ M_\odot$ leads to a next-generation with a metallicity of [Fe/H] $= -3.25$. A maximum of [Fe/H] $= -2.25$ would then be present as a result of 10 such SNe, and should reflect the average metallicity of the system.

Large abundance spreads in [X/H] are expected due to incomplete mixing on the short dynamical timescale within the center of the first galaxy (Greif et al. 2010). The second-generation starburst will occur on roughly this timescale, so that metallicity inhomogeneities in the gas will be reflected in the respective stellar abundances. We note that any inhomogeneous mixing occurring in a system would primarily affect element ratios containing H, i.e., [X/H], but to a much lesser degree those with two heavy elements, i.e., [X/Fe], assuming that no differential mixing takes place on length and time scales relevant for star formation. Hence, any spread, for example in [Fe/H], is possible, but little or no scatter in, e.g., [α/Fe]. *Consequently, large variations of Δ [Fe/H] $\sim$ 1 dex or more around the average systemic metallicities of [Fe/H] ~ -2.3 are expected to occur.*

The core-collapse ejecta (e.g., Heger & Woosley 2010) have well-correlated Fe and α-abundances (Mg, Ca, Ti, Si), resulting in the characteristic metal-poor halo star signature of [α/Fe] $\sim$ 0.35 (Cayrel et al. 2004). This abundance level is shown in Figure 1 in the middle panel, and reproduced in the top and bottom panels. In contradistinction, the bottom panel shows abundances of stars in the classical dwarf galaxies whose chemical enrichment proceeded on a slower timescale. Hence, stars with α-abundances below the halo value are found at lower metallicities than [Fe/H] ~ -1.0. Again, this behavior is reproduced in the top panel of the figure. We also show the currently available abundance data of stars in the UFDs, which we discuss below and in Section 4.

The halo and dwarf galaxy stars thus clearly show the standard "multi-shot" enrichment histories enabled by many generations of SNe, i.e., extended phase(s) of chemical evolution and star formation. Such normal chemical evolution is reflective of feedback processes having a much less severe, or even no, impact on the existing conditions of the host galaxy.

Following the one-shot scenario with enrichment by massive Pop III stars, for the first galaxies, we therefore predict average values of [α/Fe] as set by the sample of Cayrel et al. (2004) with a range of $\pm$0.1 dex (approximately, the measured standard deviation). *A first galaxy should thus contain no stars, not even at higher metallicity ([Fe/H] $>\sim -2.0$), that show α-abundance ratios systematically less than the halo value or even with the solar ratio, [α/Fe] $=$ 0.0. This behavior is illustrated in Figure 1 (top and bottom panels).* Such low values would indicate star formation after any of the more massive Pop II stars eventually exploded as SNe Ia, adding iron to the galaxy, in contradiction to the one-shot assumption.

The top panel in Figure 1 thus summarizes the basic three possible enrichment histories for a given galaxy.

Late-time AGB or SN Ia enrichment from lower mass stars would eventually occur in a one-shot system, but only after the initial Pop II starburst, and after the remaining gas was blown out of the system (see the discussion in Section 2). *Consequently, there should not be any signs of general s-process enrichment by*

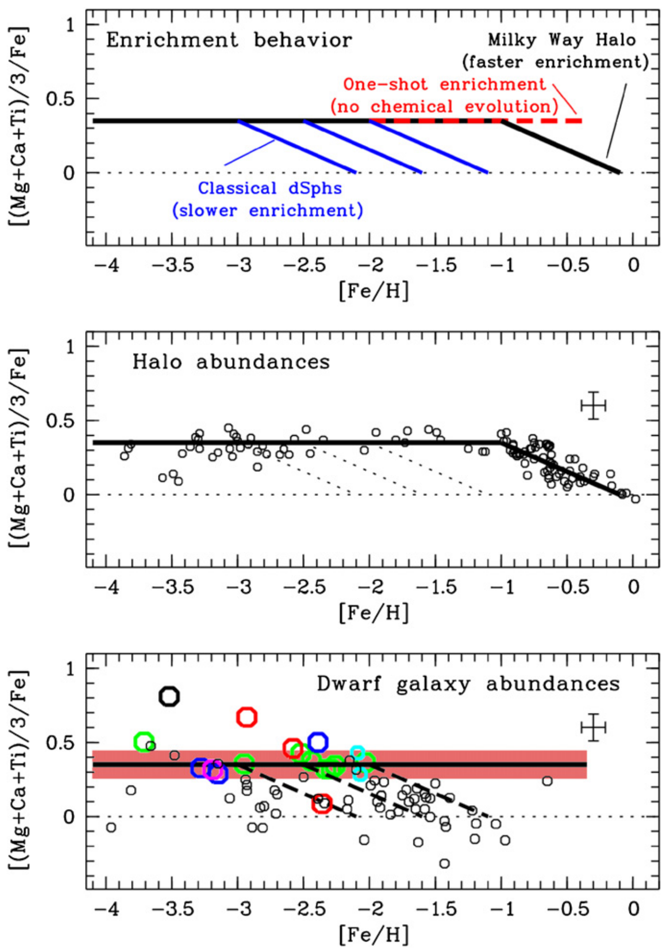

Figure 1. Top: schematic representation of chemical enrichment in [α/Fe] vs. [Fe/H] plane. The behavior for the Milky Way and dSph galaxies are shown together, with our prediction for a one-shot enrichment with no subsequent chemical evolution. The schematic behavior for the Milky Way and the dSphs has been deduced from the metal-poor data in the two lower panels. A combined Mg-Ca-Ti abundance is used to represent the α abundance typical for core-collapse SNe enrichment. The dotted line indicates the solar ratio. Middle: high-resolution α-abundances of metal-poor stars from Cayrel et al. (2004) (halo) and Fulbright (2000) (thin/thick disk). The diagonal dotted lines indicates the enrichment behavior of the dSph galaxies (see bottom panel), which differs from that of the Milky Way. A representative uncertainty is shown. Bottom: high-resolution α-abundances of metal-poor stars in the classical dSph (small open black circles and several evolutionary path are indicated with dashed lines; Shetrone et al. 2001, 2003; Fulbright et al. 2004; Geisler et al. 2005; Aoki et al. 2009; Cohen & Huang 2009; Frebel et al. 2010a; Tafelmeyer et al. 2011) and UFD galaxies (Feltzing et al. 2009; Frebel et al. 2010b; Norris et al. 2010c; Simon et al. 2010; Norris et al. 2010a). Different colors denote different UFD galaxies. Open red circles: Coma Berenices, blue: Ursa Major II, pink: Leo IV, cyan: Hercules, green: Bootes I, and black: Segue 1. The pink shaded region around [α/Fe] $= 0.35$ depicts the predicted one-shot enrichment behavior (with 0.1 dex observational uncertainty) as set by the α-element enrichment caused by core-collapse SNe only.

(A color version of this figure is available in the online journal.)

AGB stars, despite the fact that some of these Pop II stars with intermediate masses must have gone through an AGB phase to later provide s-process material as well as carbon. The only exceptions would be individual metal-poor stars with strong *s*-process (and carbon) enhancements due to a mass transfer across a binary system.

If an *r*-process occurred in one of the core-collapse SNe (e.g., one with a 10–20 $M_\odot$ progenitor), small amounts of neutron-capture material would be produced. Unfortunately, no theoretical *r*-process yields are available for direct comparison with observations. The one exception is the "weak" *r*-process investigation by Izutani et al. (2009), focusing only on the production of the light neutron-capture elements Sr, Y, and Zr. For two different progenitor masses and "normal" explosion energy of $E_{51} \sim 1$, their models yield Sr ejecta of $M(\mathrm{Sr}) \sim 1 \times 10^{-8}\,M_\odot$ (their 13 $M_\odot$ model) and $M(\mathrm{Sr}) \sim 1 \times 10^{-7}\,M_\odot$ (25 $M_\odot$ model), with respective Fe yields of $M(\mathrm{Fe}) \sim 6 \times 10^{-2}\,M_\odot$ and $M(\mathrm{Fe}) \sim 2 \times 10^{-1}\,M_\odot$. Diluting these yields in $10^5\,M_\odot$ of H gas, yields low values of [Sr/H] ~ -5.8 and -4.8 depending on the model. The corresponding [Sr/Fe] values are ~ -2.3 and -1.9, with corresponding [Fe/H] values of -3.5 and -2.9. Their higher explosion energy 25 $M_\odot$ model produces more Sr (which they conclude to be the appropriate progenitors for their group of "weak" *r*-process stars), although the results appear to be very sensitive to model parameters. Considering just their "normal"-energy SN yields, very low levels of [Sr/Fe] must have been present in a first galaxy. By extension, [Ba/Fe] values must have been even lower, assuming the ratios of [Sr/Ba] ~ 0.4 of typical stars in the halo sample (François et al. 2007).

We arrive at a more general, heuristic limit on the *r*-process contribution in a first galaxy, specifically on the Sr and Ba abundances, as follows: In the MW, the *s*-process is known to dominate the chemical evolution of neutron-capture elements above [Fe/H] > -2.6 (Simmerer et al. 2004), as provided by AGB stars. We use metal-poor stars from the literature to estimate the general trends of [Sr/Fe] and [Ba/Fe] in stars with $-2.6 <$ [Fe/H] < -1.7. These stars characterize early gas clouds that were significantly enriched in *s*-process elements. *Consequently, stars with abundances lower than the general trend can be regarded as representing either an early enrichment by the very first individual AGB stellar winds or an r-process enrichment as provided by core-collapse SNe, in the same way as for stars at lower metallicities before the onset of any AGB enrichment.* These lower-than-average values are [Sr/Fe] < -0.5 and [Ba/Fe] < -1.0, as indicated in Figure 2. Also shown are the abundances of halo, classical dwarf galaxy and UFD stars. These empirical limits are somewhat higher than the values derived from the Izutani et al. (2009) calculations, but they represent a more robust upper limit to a pure *r*-process enrichment by core-collapse SNe.

We now consider the yields of a PISN, in addition to core-collapse SN enrichment, and how they would change the chemical make-up of a first galaxy. There are two main chemical signatures expected to be found in metal-poor stars if a PISN had enriched the system as well. Since there are 10 independent star-forming halos (the ∼10 progenitor minihalos that merge to form the first galaxy), it is very likely that the PISN will be accompanied by up to ∼10 core-collapse SNe. *Consequently, the previously described enrichment pattern would be present, but additionally, individual stars would display a more or less clean PISN signature.* The strength of the PISN signature in a given star will depend on the details of the stochastic, inhomogeneous mixing of the ejecta from all contributing SNe (Karlsson et al. 2008). Due to nearly constant yields of C, Mg, and Ca independent of the progenitor mass (Heger & Woosley 2002), respective next-generation stellar abundances would be high, e.g., [Ca/H] ~ -2.0, albeit with a spread of ± 0.5 dex. Fe, on the other hand, with almost arbitrary yields, is not directly predictable. With increasing progenitor mass, vast quantities of Fe, and also O, are produced, up to several tens of solar masses (see Figure 1 in Heger & Woosley 2002). Consequently, such a star could have [Fe/H] ~ -3.0 or even

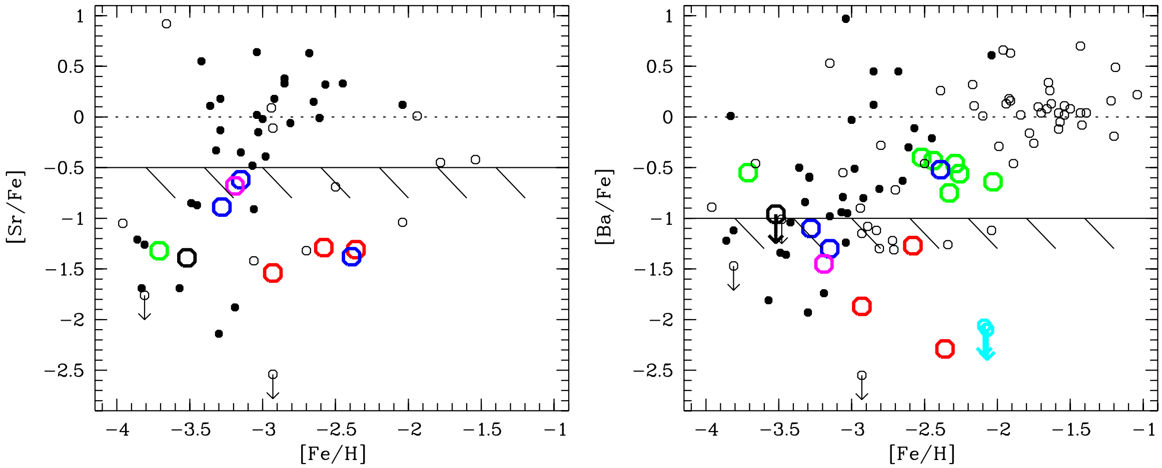

Figure 2. High-resolution neutron-capture abundance ratios [Sr/Fe] and [Ba/Fe] of UFD galaxy stars as a function of their metallicities [Fe/H], in comparison with halo and dSph galaxy stars. Robust upper limits for a potential *r*-process enhancement are indicated by the solid horizontal lines in each panel (see the text for discussion). Large open circles show different UFD galaxies; see Figure 1 for a description. Filled black dots represent halo stars (Cayrel et al. 2004; François et al. 2007). Small open black circles show the abundances of stars in the classical dSph galaxies.

(A color version of this figure is available in the online journal.)

less, or [Fe/H] ~ -1.0 or more. Either way, the [Mg/Fe] and [Ca/Fe] ratios would likely differ from that of typical halo stars. *Another characteristic signature of PISN-enriched gas is a complete lack of neutron-capture elements. Hence, any star formed from such material would have no detectable neutron-capture elements.*

4. THE DWARF GALAXY ARCHAEOLOGICAL RECORD

In Figures 1 and 2, we have summarized the currently available abundances obtained from high-resolution spectroscopy of stars in several UFDs as well as halo stars. We show [α/Fe] as a tracer of core-collapse enrichment (Figure 1, top), and the neutron-capture elements [Sr/Fe] and [Ba/Fe] as a gauge for pure *r*-process material (Figure 2). We have presented our predictions for the chemical signatures in a first galaxy, following the one-shot enrichment of the system as part of its assembly from Pop III hosting minihalos. For convenience, we briefly summarize these predictions again:

1. Only SNe from the first generation of stars would contribute to the chemical inventory of a first galaxy.
2. Inhomogeneous mixing would lead to large variations of Δ[Fe/H] ~ 1 dex or more around the average systemic metallicities.
3. A first galaxy should contain no stars, not even at higher metallicity ([Fe/H] $>\sim -2.0$), that show α-abundance ratios systematically less than the Galactic halo abundance value of [α/Fe] ~ 0.35.
4. No general signature of *s*-process (+ carbon) enrichment from AGB stars should be identifiable in the surface abundances of long-lived low-mass stars in a first galaxy.
5. If PISN also occurred in a first galaxy, then in addition to the previous points, individual stars would display a PISN signature, i.e., high [α/Fe] values very different from that of halo stars.
6. A complete lack of neutron-capture element enrichment by PISN would lead to next-generation stars with no detectable neutron-capture elements.

Based on these predictions, we can now asses whether any of the surviving UFDs chemically resemble a one-shot enrichment first galaxy.

We begin with enrichment by core-collapse SNe. To what extent do the UFD stars show an [α/Fe]-enhancement of $\sim$0.35 dex, especially at metallicities of [Fe/H] > -2.5? This signature has indeed been found for most stars in the UFDs that have detailed chemical abundances available, and it has been suggested that the observed elements originated from canonical core-collapse events in the same way as found for halo stars (e.g., Frebel et al. 2010b; Simon et al. 2010). Unfortunately, not many metal-rich stars are present and also observable in these systems, resulting in no data at [Fe/H] > -2.0.

Bearing in mind that only one calculation of *r*-process yields is currently available, the prediction of low neutron-capture abundances is in reasonable agreement with the overall depleted abundances of Sr and Ba (e.g., many stars have [Ba/Fe] < -1.0) in all of the UFDs. We also note that no metal-poor star with *s*-process enhancement from a binary mass transfer has yet been conclusively identified in any of the known UFDs.[3] Recent medium-resolution spectroscopic studies (Kirby et al. 2008; Norris et al. 2008, 2010b) showed that all of the UFDs have large [Fe/H] spreads of $\sim$1 dex or more, and reaching below [Fe/H] $= -3.0$. Moreover, some have average metallicities as low as [Fe/H] ~ -2.6 (Leo IV, Hercules), which is less than that of the most metal-poor globular clusters. None of the systems with $L_{\rm tot} \lesssim 10^5\, L_\odot$ have averages of [Fe/H] > -2.0. These low metallicities agree well with the estimates for Fe enrichment from up to 10 core-collapse SNe in a first galaxy. The large abundance spread is also in agreement with simulation results, reflecting inefficient mixing.

Out of the six UFDs with available abundance data, Ursa Major II (blue) best fulfills the criteria for being a candidate first galaxy fossil. The one star with a higher Ba abundance is possibly an externally enriched binary star, so no strong conclusions can currently be derived from this object. Coma Berenices (red) and Bootes I (green) are good candidates as well, although the Bootes I stars have higher Ba abundances than our limit, and Coma Berenices' highest metallicity star shows a decreased [α/Fe]. However, future *r*-process predictions will

[3] Frebel et al. (2010b) found a star with apparent radial velocity variations (two measurements only) which is possibly *s*-process enhanced. A clarification, however, would require measurements of additional neutron-capture elements.

reveal whether this is necessarily inconsistent with a one-shot enrichment. Intriguingly, Hercules (cyan) appears to be different. Not shown in Figure 1 (bottom panel) are the Ca abundances of several stars (Adén et al. 2011), which show large variations ranging from subsolar to [Ca/Fe] ~ 0.3. We tentatively rule out Hercules as a candidate, along the same line as the more luminous classical dwarfs. We note, however, that Adén et al. (2011) had one star in common with Koch et al. (2008), but derived a 0.4 dex lower Ca abundance, which is their lowest value in the sample. This is somewhat puzzling, but given that the Ca spread is about twice the discrepancy, it seems reasonable to assume that this galaxy indeed has a significant abundance spread in this element. Leo IV (pink) and Segue 1 (black) at present contain too few data to arrive at a meaningful conclusion. Hence, additional high-resolution abundance studies of more stars in each of these as well as other systems are required. But new Segue 1 results (A. Frebel et al. 2012, in preparation) already indicate this system to be in agreement with a pure core-collapse SN enrichment. Only with more metal-rich stars can it be revealed whether the one-shot conjecture holds or if evidence for extended star formation and chemical evolution can be found. Either result would provide important constraints on early feedback processes.

Are there any hints for a potential PISN enrichment? Since the faintest galaxies have very low average metallicities and truncated star formation, UFDs provide the perhaps best chance to ever detect the chemical signature of a PISN event. Identifying the PISN signature is, however, difficult given that the predicted very high yields may lead to stars with much higher metallicity compared with a regular core-collapse enrichment (see Karlsson et al. 2008). Even if a first galaxy did not survive until the present time, it is likely that individual stars that formed in these environments passed into larger systems through merger events, possibly into surviving galaxies, e.g., Hercules with $\log(L/L_\odot) = 4.6$, or more luminous systems such as Draco and Sculptor. Hence, individual stars in systems more luminous than the faintest UFDs with extensive star formation and chemical evolution could still preserve the rare signature of PISNe.

One interesting galaxy in this context is Hercules, for which Koch et al. (2008) measured the abundances of many elements of two member stars. Both Ba limits are [Ba/Fe] < -2.1, and among the lowest values ever measured.[4] While the average metallicity of Hercules is [Fe/H] ~ -2.6 (but with a spread of more than $\sim$1 dex in Fe; Kirby et al. 2008; Adén et al. 2011), these two stars have rather high metallicities of [Fe/H] ~ -2.0. Both stars have high Mg/Fe ($\sim$0.8) and low Ca/Fe ratios ($\sim$0.05), but their Ti/Fe corresponds to the typical halo value. Koch et al. (2008) speculated that in order to produce large Mg/Ca ratios in a "next-generation" star (i.e., the observed star), Hercules would have to have been enriched by fewer than 11 core-collapse SN events, consistent with our picture of first galaxy enrichment. Considering the above PISN enrichment criteria, Hercules could be a candidate site for a PISN pre-enrichment, and for testing the predictions for PISN yields (Karlsson et al. 2008). However, the recent low stellar Ca/Fe abundances of Adén et al. (2011) in Hercules complicate the situation, and indicate that this system is not a candidate first galaxy. Additional observations will be helpful to fully understand the chemical evolution of this galaxy.

[4] It should be noted that these stars with [Ba/H] < -4.15 do not have the lowest [Ba/H] values or limits. Many halo stars have abundances [Ba/H] $\leqslant -5.0$ ($\sim$10 stars found in the compilation of Frebel 2010; e.g., from François et al. 2007; Lai et al. 2008).

Another interesting case is a star with [Fe/H] ~ -3.0, located in the classical dSph Draco, and having an upper limit of [Ba/Fe] < -2.6 (Fulbright et al. 2004). Strontium is similarly depleted and no other neutron-capture elements could be detected. On the contrary, all other, more metal-rich stars in Draco do not show this behavior (Cohen & Huang 2009). This star is thus highly unusual, but similar to the stars in Hercules, except for its lower metallicity. This difference might be due to the arbitrary Fe yields of PISNe, inhomogeneous mixing or simply the gas mass available for mixing, which could be $\sim$10 times more than in a Hercules-like object. Fulbright et al. (2004) found that no ordinary SN model could account for the lack of neutron-capture elements in this star, and its origin is still uncertain. Given that this galaxy is only $\sim$10 times more luminous than Hercules, and thus lies on the low-luminosity tail of the classical dSphs, it could plausibly have assembled from several first galaxies. Hence, some individual stars could have preserved their PISN signature throughout their cosmic merger journey while showing signs of extended star formation at the same time.

5. CONSTRAINTS ON THE NATURE OF FIRST GALAXIES

Next to atomic cooling halos, minihalos have been suggested as UFD progenitors (e.g., Salvadori & Ferrara 2009; Bovill & Ricotti 2009). The minihalo environment may, however, face a problem, at least for the lowest-mass minihalos that are close to the threshold mass ($\sim 10^6\ M_\odot$) required for H_2 cooling to become effective. In such minihalos, the available gas mass is only 10^3–$10^4\ M_\odot$ (e.g., Yoshida et al. 2006), much lower than in the more massive atomic halos. Consequently, any SN yield is much less diluted, generally resulting in stars with higher metallicity than those in atomic cooling halos. Diluting 0.1 $M_\odot$ of Fe into the available gas mass yields a next-generation star with [Fe/H] ~ -1.2 (for $10^3\ M_\odot$). Even the assumption that inhomogeneous mixing would be able to produce a spread of ± 1 dex around this value could not explain extremely metal-poor stars with [Fe/H] < -3, including the most metal-poor star in any UFD, BooI-1137 with [Fe/H] ~ -3.7 (Norris et al. 2010c). The only possibility would be to limit the maximum Fe SN yield to $\sim 0.001\ M_\odot$ (or 0.01 $M_\odot$ for the larger dilution mass of $10^4\ M_\odot$) in any minihalo in the early universe. Atomic cooling halos with their larger gas reservoirs thus appear, at least broadly, to be able to account for the existence of the lowest-metallicity stars.

We point out that the minihalos invoked as UFD progenitors (Salvadori & Ferrara 2009; Bovill & Ricotti 2009) typically lie at the high mass end of the minihalo range, thus largely circumventing this mixing problem as well. Within the minihalo scenario, the same system would have to first lead to the explosion of Pop III SNe, subsequently reassemble the enriched gas inside its shallow potential well, and finally trigger a second generation of star formation. For the atomic cooling halo pathway, on the other hand, the sites for first and second generation star formation are decoupled, thus alleviating the problem of admitting Pop III pre-enrichment. Altogether, we thus favor the atomic cooling halo path that can more readily explain the presence of metal-poor stars. We stress, however, that there will be a continuum of more complex enrichment histories, where multiple SN generations and contributions from low-mass stars, corresponding to host systems of subsequently larger mass, and therefore deeper potential wells (for an alternative view, see Strigari et al. 2008). Observationally, this sequence of cosmological formation sites corresponds to the progression from the lowest-luminosity dwarfs, to classical dwarf spheroidals, and to Magellanic-Cloud-type irregulars.

Assuming that the UFDs are chemical one-shot events, the observed spread in Fe (i.e., [Fe/H]) suggests that mixing in these early systems was inefficient. Otherwise, all stars would have nearly identical abundances, similar to what is found in globular clusters (e.g., Gratton et al. 2004). We can thus infer that mixing in the very first galaxies was largely incomplete, whereas globular clusters must have formed in much different environments where turbulent mixing would have been much more efficient. We repeat that such inefficiency would not yield a scatter in the elemental abundance ratios [X/Fe], unless differential mixing among different elements played an important role.

Hercules, having the highest luminosity of the examined systems, exhibits an abundance behavior, e.g., a large spread in Ca, that suggests possible SN Ia enrichment. We therefore derive an upper limit to the luminosity for candidate first galaxies of $\log(L/L_{\odot}) \sim 4.5$. Bootes I, with a similar luminosity will be an interesting object in this regard, and additional observations will show if this system remains a good candidate. It is interesting to note that Coma Berenices has recently been shown to be a stable UFD with no signs of tidal stripping (Muñoz et al. 2010), while Ursa Major II appears to currently undergo disruption. As for Leo IV, Simon et al. (2010) suggested that its entire Fe content could have been provided by a single SN. If confirmed with additional observations, the case of Leo IV would show that one-shot events do take place, and that such simplistic galaxies, like the first galaxies, can survive to the present day.

6. DISCUSSION AND CONCLUSIONS

The currently known UFD abundance record leads us, with the caveats and qualifications discussed above, to derive the following conclusions. Independent of the question of whether UFDs are surviving minihalos or atomic cooling halos, we suggest that at least some of today's UFDs (Ursa Major II, Leo IV and possibly also Coma Berenices, Bootes I) are likely to have been the results of chemical one-shot events that occurred in the early universe. Given that atomic cooling halos seem to be the more favorable environments for producing low-metallicity stars that resemble the observed stellar populations of the UFDs, these systems are plausible formation sites for the least luminous galaxies.

As additional chemical abundances of individual dwarf galaxy stars are measured, abundance gradient studies of the UFD galaxies will further constrain the mixing efficiency. Stronger gravitational fields in the center of a system would drive more turbulence that in turn would induce mixing. To properly interpret the data, in particular for future observations with extremely large telescopes, the expected signature of clustered star formation in the first galaxies needs to be taken into account (Bland-Hawthorn et al. 2010). Since the UFDs are ideal testbeds for various feedback processes, it will also be interesting to study the carbon enrichment and the spread of carbon abundances in these systems. Carbon, as well as oxygen, may have been a key cooling agent inside the first galaxies (Frebel et al. 2007). One extremely carbon-rich star (with $[Fe/H] \sim -3.5$) has already been found in Segue 1 (Norris et al. 2010a). This is consistent with the predictions by Frebel et al. (2007), but moreover, it adds to the evidence that massive Pop III stars may have been the progenitors of carbon-rich metal-poor stars. If stars with extremely low [C/Fe] and [Fe/H] can be found, as has recently been done in the Milky Way (Caffau et al. 2011), then it would provide additional insights into early star formation in primitive high-redshift halos.

The existence of such one-shot enrichment sites can be refuted with future observations of UFD stars revealing the signatures of, e.g., *s*-process enrichment or $[\alpha/Fe]$ abundance ratios systematically lower than the halo value of $[\alpha/Fe] = 0.35$ in these galaxies. However, we would still have gained crucial empirical constraints for the next generation of ab initio cosmological simulations that will be able to resolve the fine structure of star formation and feedback. In the latter case, dwarf galaxy archaeology would have indicated that negative feedback is not able to completely suppress the ongoing formation of stars. Simulations could then adjust their treatment of feedback accordingly. Alternatively, the absence of any one-shot systems could simply indicate that we have not yet discovered the true survivors of the first galaxies.

Simulations with extremely high-resolution that will study the fine-grained turbulent mixing of metals on scales of a few AU will soon become feasible. The dwarf galaxy archaeological comparison between UFDs and early star-forming halos is thus important for providing constraints as well as consistency checks for state-of-the-art simulations. The emerging field of dwarf galaxy archaeology, which closely connects chemical abundances and galaxy formation models, promises a more complete understanding of galaxy formation and evolution at the end of the cosmic dark ages.

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